EVALUATION OF SUPERPLASTIC FORMING AND WELD-BRAZING FOR FABRICATION OF TITANIUM COMPRESSION PANELS

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ABSTRACT

Studies have been conducted at NASA Langley Research Center to demonstrate the processing advantages of superplastic forming and weld-brazing for the fabrication of full-size titanium skin stiffened structural components. The studies were conducted in three phases. The initial phase included fabrication and testing of 10-inch-long single stiffener compression panels of varying configurations, including advanced designs to explore improved structural efficiency. The second phase consisted of scaling up the process to fabricate and test multiple stiffener panels approximately two ft by three ft in area. The panel configurations selected for evaluation included a conventional hat stiffened design and the beaded web hat stiffened design which exhibited highest structural efficiency in the initial phase results. The multiple stiffeners for each panel were superplastically formed in a single operation from a single sheet of titanium and then joined to a titanium skin by weld-brazing.

In the third phase of the study, an alternative approach (designated the half-hat process) was developed for superplastically forming and weld-brazing the titanium compression panels. This process involved superplastically forming individual half-hat stiffener segments which minimized thinning of the titanium compared to results obtained in the earlier phases. The half-hat segments were then incorporated into full-size compression panels by weld-brazing the segments to titanium caps.

Results from these studies verify that the superplastic forming process can be designed and controlled to provide close tolerances, and that weld-brazing is a highly effective joining technique for fabrication of full-scale, full-size compression panels.

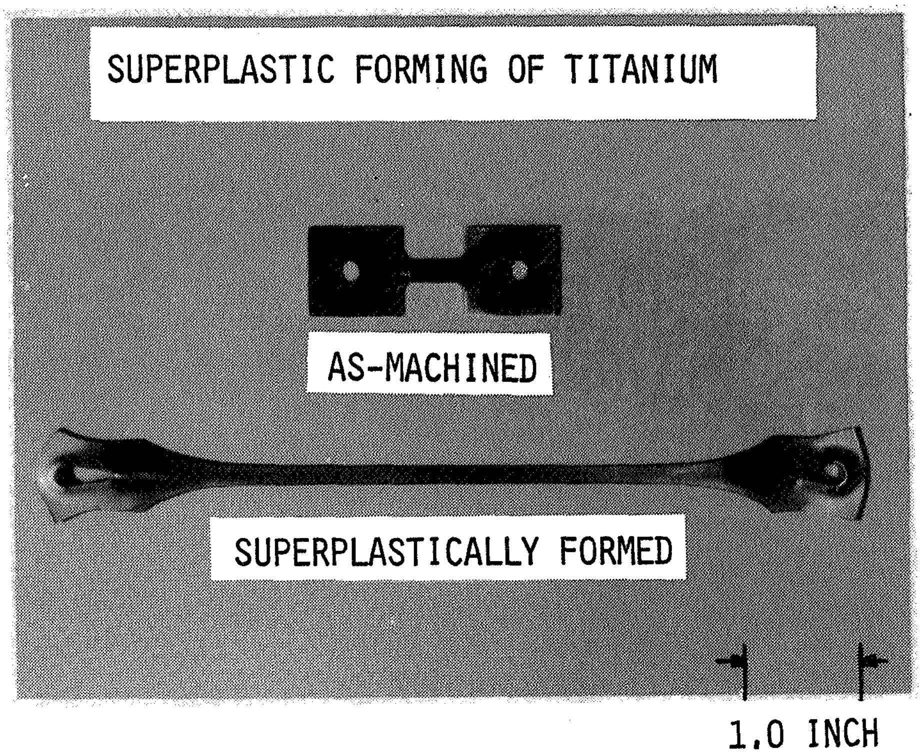
SUPERPLASTIC FORMING/WELD-BRAZING (SPF/WB) PROCESS

INTRODUCTION

- o INITIAL DEVELOPMENT
- o SCALE-UP
- o REFINEMENT

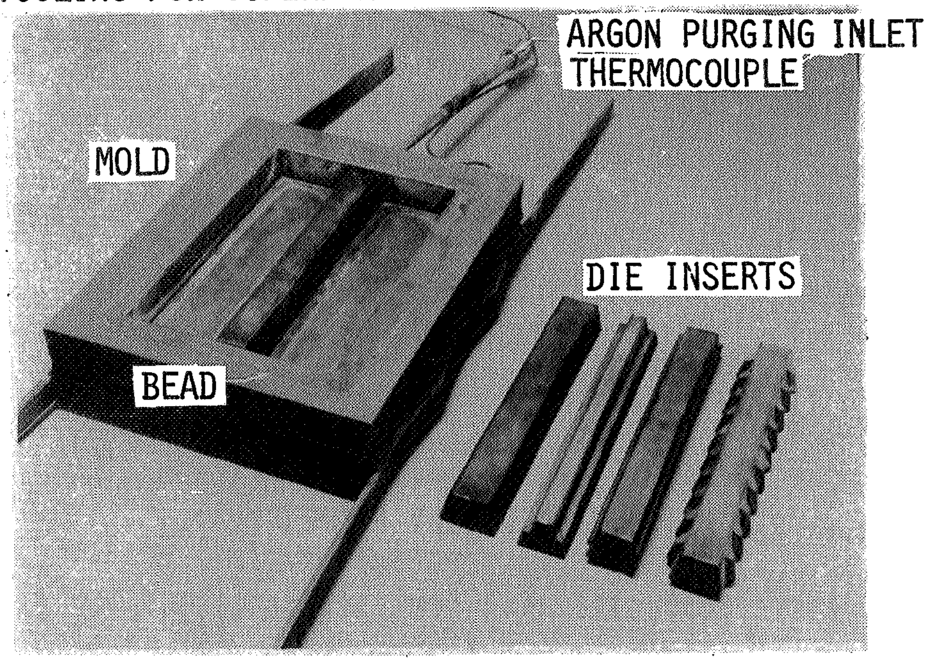
In the past few years the aerospace industry has been involved in the research and development of the advanced forming and joining method for titanium alloys known as superplastic forming and diffusion bonding. The research at the Langley Research Center (LaRC) of NASA has taken a different approach where superplastic forming was combined with weld-brazing to fabricate structural hardware. This is a summary paper on this long-standing in-house research program.

This paper discusses the research program beginning with the initial process development phase that demonstrated that single stiffener structural panels of advanced design could be fabricated by the superplastic forming/weld-brazing process and that these panels could be used to explore structural efficiency. The second phase of the program was to scale-up the process to fabricate full-size panels having multiple stiffeners. In the recent phase of the program the superplastic forming/weld-brazing process was refined in an attempt to reduce metal thinning during superplastic forming.



The NASA LaRC program combined two established titanium alloy forming and joining processes, superplastic forming and weld-brazing. The superplastic forming of titanium alloys has been researched by the aerospace industry for several years. To demonstrate and develop the superplastic forming process, the initial work was usually done on tensile specimens. The figure shows a Ti-6Al-4V titanium alloy tensile specimen in the "as-machined" condition and after being "superplastically formed." In the as-machined condition the test section is one-half inch long. The superplastically formed specimen has been elongated approximately 1100 percent by heating the specimen to 1700°F and loading at a strain rate of 0.0002 per second. Low flow stresses of one to two ksi were developed. The specimen was superplastically formed with a uniform elongation and no localized necking.

TOOLING FOR SUPERPLASTIC FORMING OF STIFFENERS

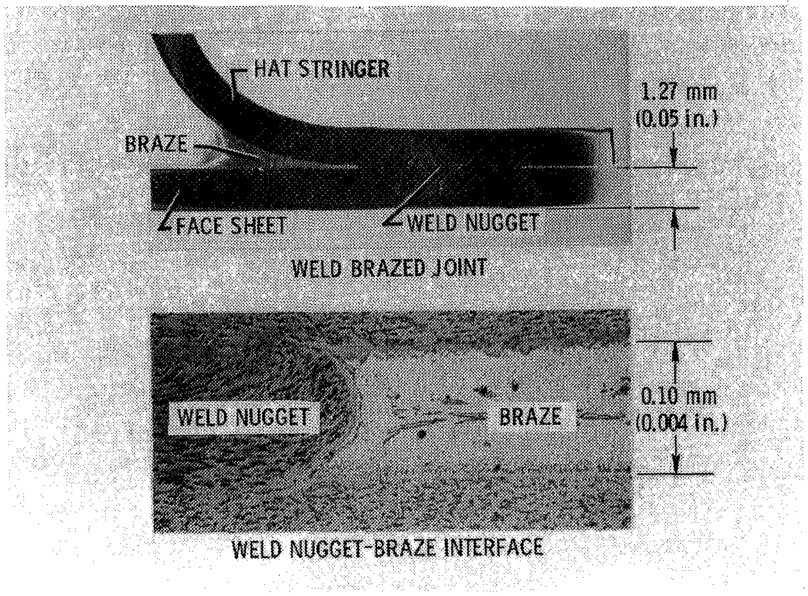


As a result of the low flow stresses required for superplastic forming, titanium sheet material can be readily blown into molds using argon gas pressure. This was the procedure utilized to fabricate stiffeners for this program (reference 1). A mold with several die inserts for the stiffener configurations evaluated is shown in the figure. The mold, machined from 2249 steel, was designed such that the titanium in the crown of the formed stiffener would equal the approximate thickness of the titanium sheet prior to forming. The resulting webs and flanges of the stiffeners had variable thicknesses due to thinning associated with superplastic forming.

The die inserts were machined from 2249 steel and positioned in the mold. One of the inserts was used to form conventional shaped hat stiffeners. The remaining die inserts were used to form stiffeners with a stepped shaped web, a ribbed shaped web, and a beaded shaped web. These complex shaped stiffeners were either difficult to form or could not be formed by conventional titanium forming methods. Stiffener shapes were selected on the basis of structural efficiency, taking advantage of the superplastic forming characteristics of the titanium alloy.

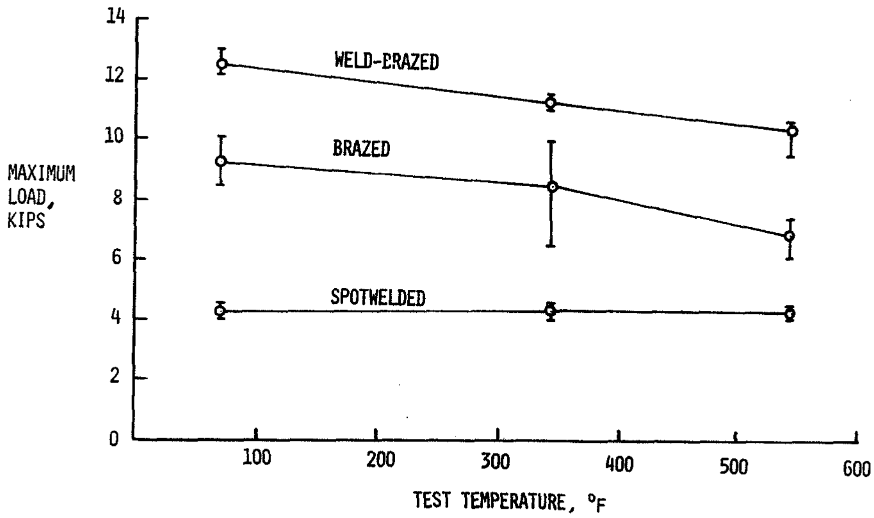
Ti-6Al-4V stiffeners were superplastically formed to the shape of the dies by placing a sheet of titanium over the lower mold. The cover plate, which has an inlet for pressurizing with argon gas, was placed over the titanium sheet. The assembled tooling was placed between heated ceramic platens mounted in a press. After the tool was heated to 1700°F, argon gas was induced through the cover plate which forces the titanium sheet into the shape of the die and lower mold cavity. Argon gas pressure was applied up to a pressure of 125 psi for a period of 90 minutes. Power to the ceramic platens was turned off and the formed titanium stiffener was cooled in the mold using argon gas.

VACUUM WELD-BRAZED JOINT



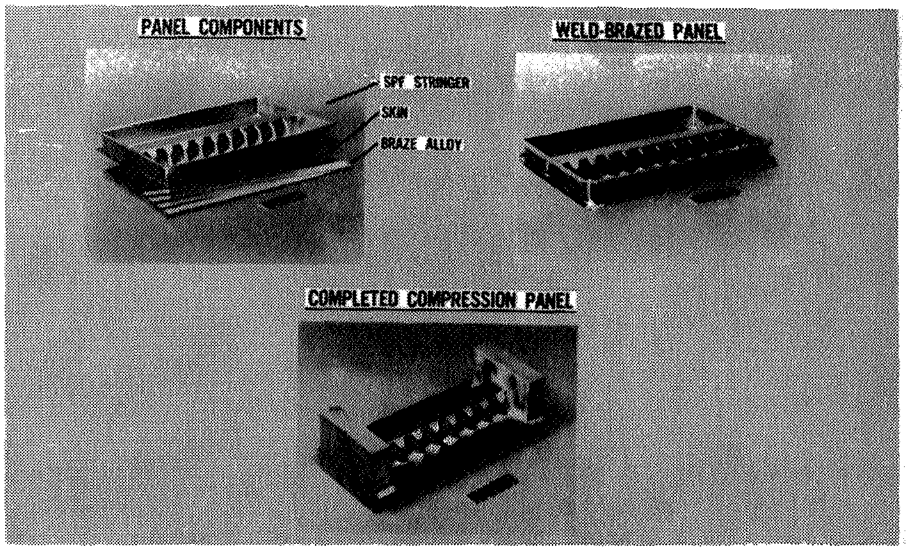
Weld-brazing was a joining process developed at NASA LaRC in the early 1970's which combined resistance spot-welding with brazing (reference 2). The process was used successfully to join titanium structural members using an aluminum braze alloy. The first step in the process was to establish spot-welding parameters which resulted in expansion of the weld nugget to provide a predetermined uniform gap between the faying surfaces in order to optimize the thickness of the subsequent brazed joint. Following resistance welding, braze alloy foil in appropriate quantities was placed along the exposed edge of the joint. The assembly was then brazed in a vacuum furnace to produce the specimen joint shown in the figure. During brazing, the braze alloy melted and was drawn into the existing gap by capillary action. The braze is shown to have drawn through the gap to form a fillet between the face sheet and the inner radius of the hat stiffener. The lower photomicrograph of the weld-brazed joint shows good integrity of the joint in the vicinity of the weld-nugget.

SINGLE-OVERLAP TENSILE-SHEAR DATA



The tensile-shear results obtained at ambient temperature, 350°F, and 550°F for titanium specimens fabricated by spot-welding, brazing, and weld-brazing are shown in the figure where the maximum load is plotted against test temperature. The data points are the average of a minimum of three tests with the data spread indicated. The tensile-shear properties of the weld-brazed specimens are shown to be greater than those of the brazed or spot-welded specimens and are approximately equal to the sum of the values shown for the spot-welded and brazed specimens. The strength of the weld-brazed specimens apparently decreases linearly with increasing temperature.

SUPERPLASTICALLY FORMED/WELD-BRAZED TITANIUM COMPRESSION PANEL

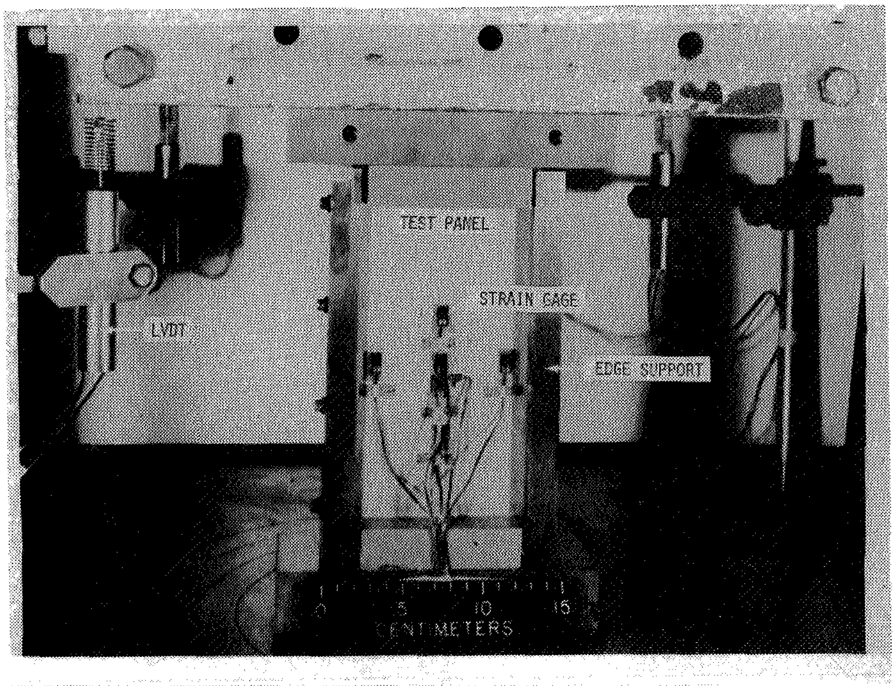


The steps involved to combine superplastic forming and weld-brazing to fabricate a compression panel are shown on the figure. The components of a panel include the superplastically formed stiffener, the panel skin and the 3003 aluminum braze alloy. Both the stiffener and skin material are 0.050-inch thick Ti-6AL-4V titanium alloy. Weld-brazing of a panel consisted of spot-welding the stiffener to the skin and then brazing. Following chemical cleaning, two rows of four spot-welds each were used to attach each flange of the stiffener to the skin. Welding parameters were developed so that weld nugget expansion established a faying surface gap 0.002 to 0.003 inches between the flanges of the stiffener and the skin. Braze alloy strips were placed adjacent to the joints to be brazed and the panel placed in the brazing furnace. Fixturing provided by the spot welds was sufficient to maintain alignment and no tooling was required for brazing of the panel.

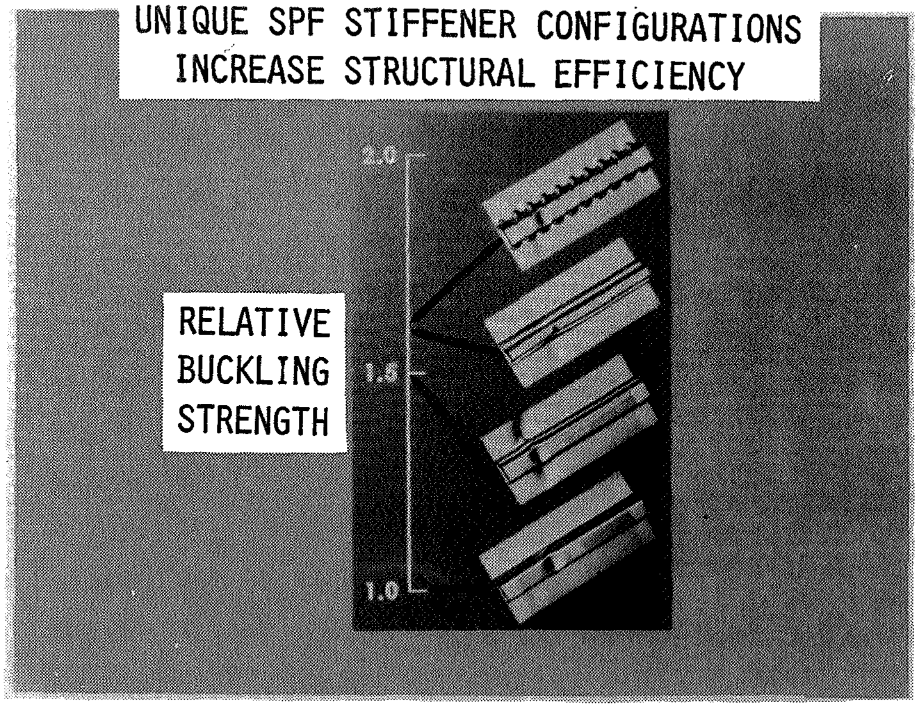
Brazing of the panel was accomplished in a vacuum furnace at a temperature of 1250°F. Upon melting, the 3003 aluminum braze alloy was drawn into the faying surface gap by capillary action. The panel was allowed to cool from the brazing temperature to room temperature before being removed from the furnace. Visual and radiography inspection verified good wetting between the stiffener and skin and establishment of a good integral joint.

Following brazing the superplastically formed/weld-brazed panel was trimmed on the edges and ends. After trimming, the panel was potted on both ends using an epoxy potting compound. Potting compound was used to facilitate grinding the ends of the panel flat, parallel to each other, and perpendicular to the skin. The potting also served to prevent local failure of the ends during compression testing.

TEST SETUP FOR SKIN-STIFFENED PANELS

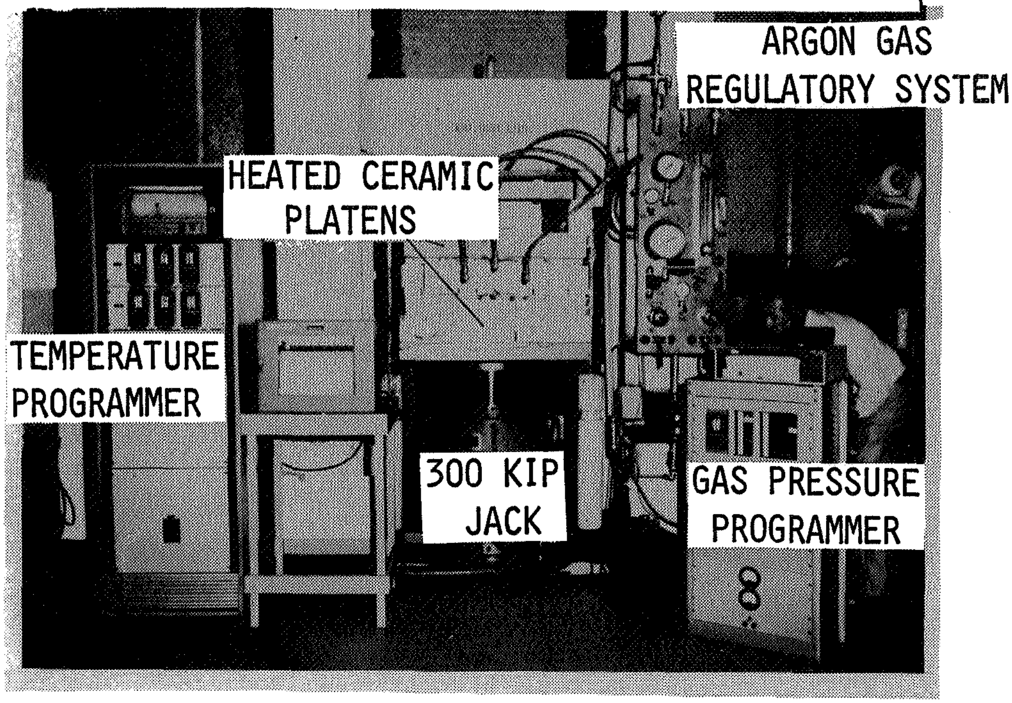


The superplastically formed/weld-brazed structural panels were tested in end compression using a 300 kip hydraulic testing machine. The edges of the panels were supported with knife edges. Relative motion between the upper and lower heads of the testing machine was measured using linear variable differential transformers. Foil strain gages were attached to the stiffener and skin and were used to measure local strains. Strain reversal was used to define onset of elastic buckling.



Three panels were fabricated and tested from each of the four stiffener configurations (conventional shaped hat, stepped shaped web, ribbed shaped web, and beaded shaped web) at room temperature. The buckling strengths of the complex shaped stiffener configurations were compared with those of the conventional shaped hat stiffener. The data in the figure show that the panels with the complex shaped stiffener configurations were 50 to 60 percent more efficient than the panels with the conventional shaped hat stiffener. This increase in structural efficiency was obtained with no increase in panel weight or cross-sectional area. The improvement in structural efficiency was attributed to the advanced structural shapes that were formed by the superplastic forming process.

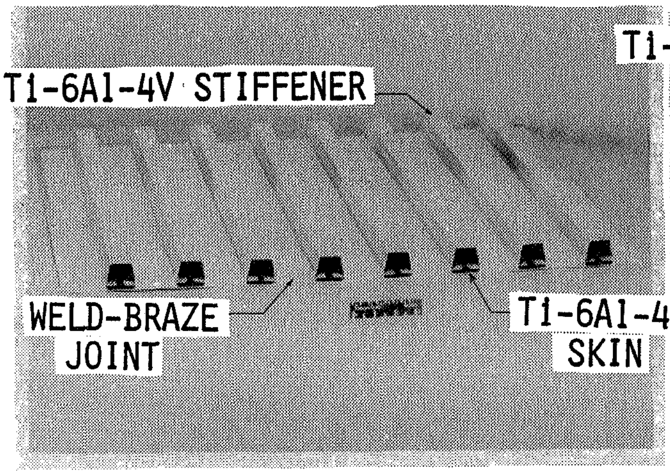
SUPERPLASTIC FORMING FACILITY



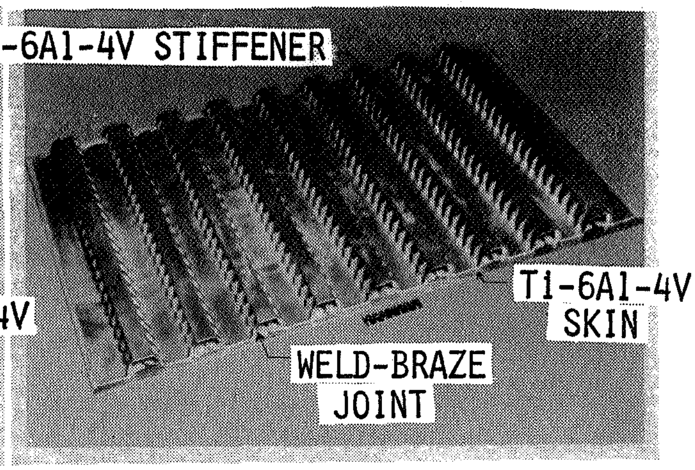
The second phase of the superplastic forming/weld-brazing program was to scale-up the process to fabricate full-size panels. The figure shows the superplastic forming facility located at LaRC. Using this facility, three-ft by two-ft multi-stiffener panels were formed with either conventional shaped hat stiffeners or beaded web shaped stiffeners. The superplastic forming temperatures and pressures were similar to those utilized in the superplastic forming of the single element panels. The ceramic platens heated the tooling to 1700°F and the 300 kip jack reacted to the gas forming pressure. Both the temperature and argon gas forming pressure were automatically programmed.

MULTIPLE STIFFENER COMPRESSION PANELS

CONVENTIONAL SHAPED HAT

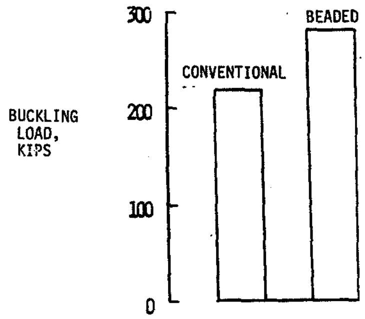


BEADED SHAPED WEB



Multi-stiffener panels were superplastically formed from one sheet of titanium in a single forming operation. The three-ft by two-ft panels with either conventional shaped hat stiffeners or beaded web shaped stiffeners are shown in the figure following weld-brazing to titanium skins. To accomplish the brazing, sufficient braze alloy was placed adjacent to each joint at both ends of the panels. Following inspection the panels were trimmed, the ends were potted, and the panels were machined to the proper length. The panels were instrumented with strain gages and tested at room temperature to failure in end compression in a hydraulic test machine.

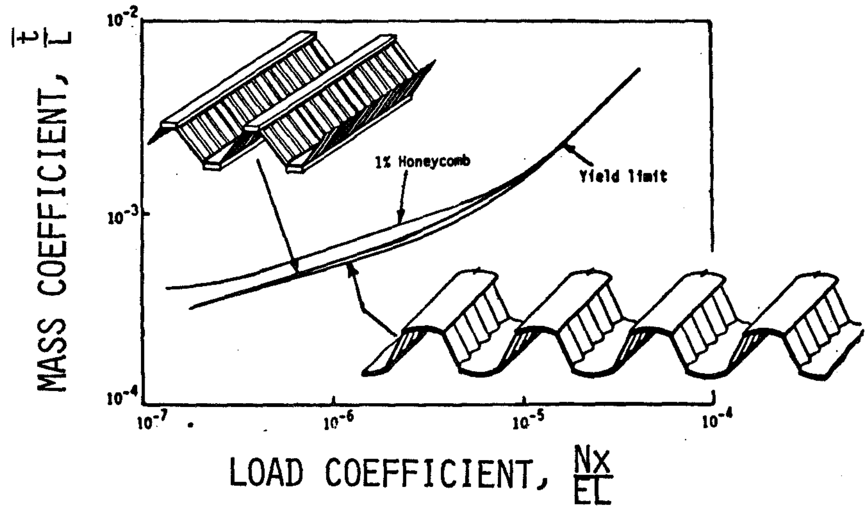
AVERAGE BUCKLING LOADS FOR SPF/WB FULL-SIZE PANELS



The buckling loads for the two full-size panel configurations are shown in the figure. The data are the average of two tests for the panel with the conventional shaped hat stiffener design and a single test for the panel with the beaded web shaped stiffener design. The panels with the conventional shaped hat stiffener buckled at an average load of 219 kips, which was in excellent agreement with analysis. An analysis of the buckling mode showed that the web of the hat was the critical element in that its local buckling strength was lower than the local buckling strength of any other element. The next lowest buckling element was the skin segment under the hat stiffener. The local buckling strength of the skin segment was calculated to be 29 percent higher than that of the webs.

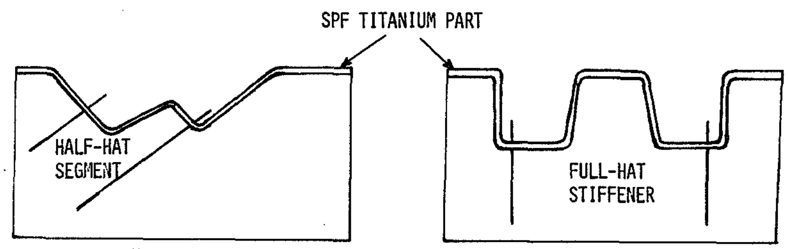
By beading the webs they become nonload-carrying structural members which made the critical element for local buckling the skin element under the beaded hat stiffener. Taking into account the reduced extensional stiffness caused by the loss of load-carrying capacity in the beaded webs, analysis predicted that the panel with the beaded web shaped stiffeners should carry 28 percent more load than the panels with the conventional shaped hat stiffeners. This was in excellent agreement with the test results that showed that the panel with the beaded web shaped stiffeners buckled at a load of 280.5 kips or 29 percent higher than the panels with the conventional shaped hat stiffeners.

ANALYSIS OF CURVED-CAP CORRUGATION INDICATES SIGNIFICANT IMPROVEMENT IN STRUCTURAL EFFICIENCY IS POSSIBLE



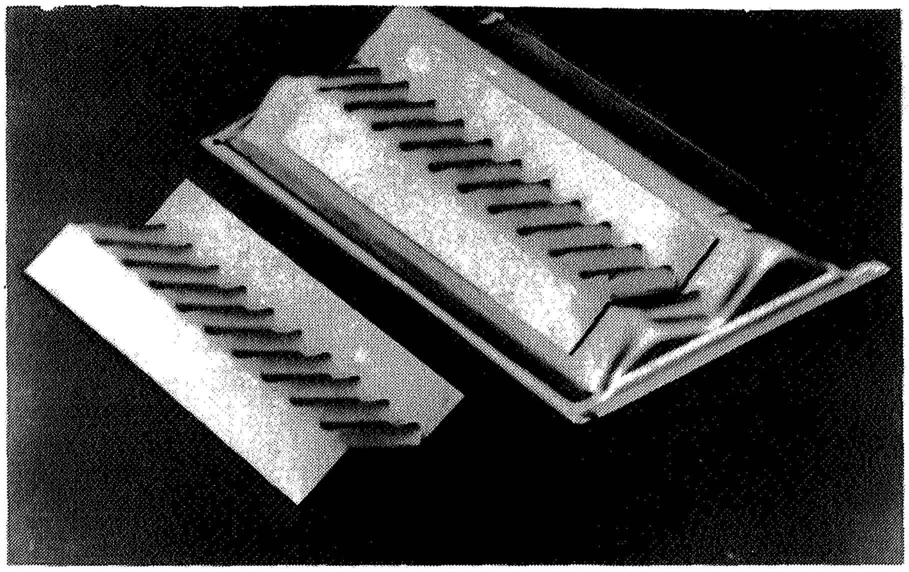
The recent phase of the program was begun by conducting an analytical study on structural efficiency of advanced panel design concepts. The results of analysis on these configurations are shown in the figure. In the mass coefficient, $\bar{t}/L$, $\bar{t}$ is the mass-equivalent thickness for the corrugated cross section and L is the panel length. In the load coefficient, Nx/EL, Nx is the compressive load-per-unit width, E is the elastic modulus and L is the panel length. The mass-strength data are dimensionless and are, therefore, independent of the materials used to make the panels. The mass-strength data for a one-percent honeycomb sandwich are a standard of comparison for low mass structures. This standard represents the desired goal in mass efficiency and is considered just beyond the current state of art in manufacturing technology. As the figure shows, some advanced configurations show mass-strength efficiencies better than one-percent honeycomb. These configurations can be fabricated with current state-of-art superplastic forming techniques. Panels fabricated using lightweight sine wave webs with minimized thinning in the flanges are an important design goal. This goal has lead to the development of new tooling for superplastic forming and a new fabrication procedure to explore the possibility of fabricating panels similar to those shown on the figure.

TOOLING CONCEPTS FOR SUPERPLASTIC FORMING



Two tooling concepts for superplastic forming stiffeners are shown in the figure. The full-hat male-die concept was utilized to form the stiffeners discussed previously in this report. After forming a stiffener, the thickness of the titanium in the crown of the stiffener was equal to the approximate thickness of the titanium sheet prior to forming. The resulting webs and flanges of a stiffener had variable thicknesses. The half-hat die concept was developed to reduce metal thinning across the web and to develop equal thicknesses in the flanges. In the half-hat die concept only half of a hat segment was superplastically formed in one operation. Two half-hat segments were weld-brazed to a cap segment to fabricate a full hat stiffener. Thinning was reduced by rotating the half-hat segment in the mold requiring lower strain levels to achieve given design dimensions than the deeper full-hat mold. The required strains or deformations were less and the effects of thinning were, therefore, minimized.

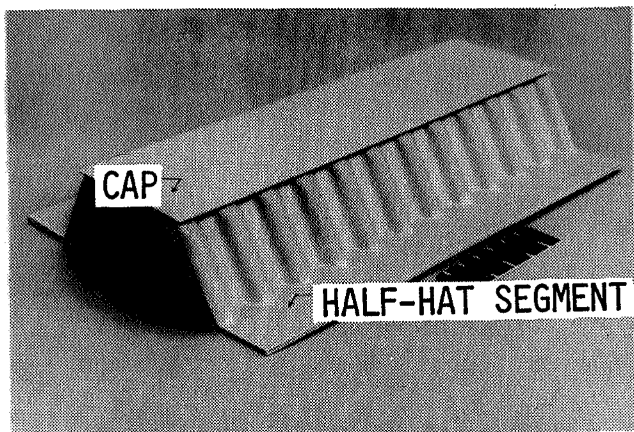
SPF TITANIUM HALF-HAT SEGMENTS



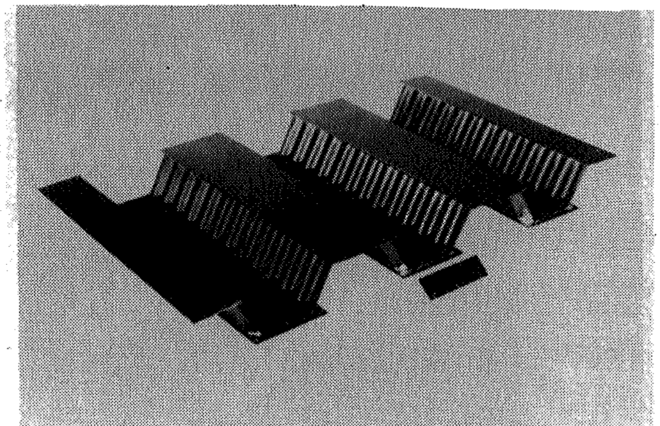
This figure shows a superplastically formed part and two half-hat segments. One half-hat segment shows the location on the part from which the half-hat segment was machined. The second half-hat segment is shown after trimming and ready for weld-brazing. A constant thickness was maintained in both flanges in the half-hat segment by using this die concept.

SPF/WB BEADED WEB COMPRESSION PANELS

SINGLE-STIFFENER

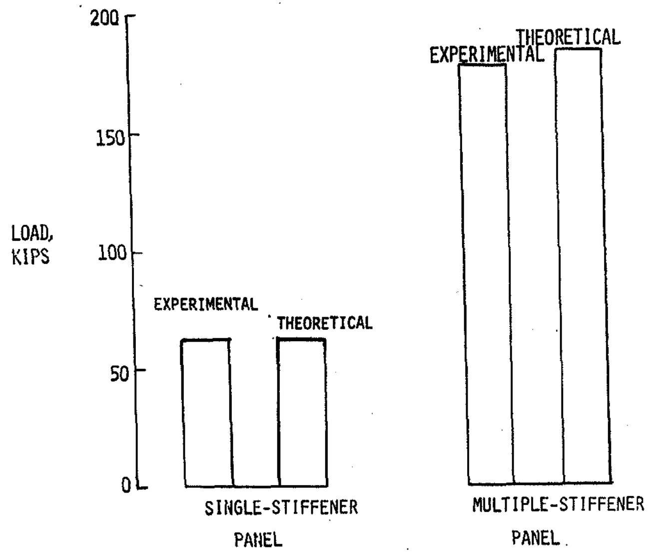


MULTIPLE-STIFFENER



The half-hat process was utilized to fabricate both single-stiffener panels and multi-stiffener panels as shown in the figure. The half-hat segments were joined to caps by the weld-braze process. The process offers the opportunity to fabricate full-size multi-stiffener panels limited only by the size of the brazing furnace. During superplastic forming of the half-hat segments, the thickness of the titanium material was reduced 16 percent from the original thickness in the highest strained regions.

AVERAGE BUCKLING LOADS OF SPF/WB PANELS USING HALF-HAT PROCESS



Following fabrication, three panels of each configuration were tested to failure in compression at room temperature. The figure shows the average buckling load and the calculated theoretical buckling load for both panel configurations. The experimental buckling load was within three percent of the calculated theoretical load for both panel configurations, verifying that the superplastic forming process can be used to achieve controlled tolerances and that the weld-brazing process was a highly effective technique for joining panel elements.

CONCLUDING REMARKS

- o SUPERPLASTIC FORMING
  - COMPLEX SHAPES
  - SIMPLE TOOLING
  - INSPECTABILITY
- o WELD-BRAZING
  - NO TOOLING
  - DUCTILE JOINTS
- o SPF/WB PANELS
  - INCREASED STRUCTURAL EFFICIENCY
  - SCALE-UP DEMONSTRATED

The two titanium processing procedures, superplastic forming and weld-brazing, were successfully combined to fabricate titanium skin-stiffened structural panels. Stiffeners with complex shapes were superplastically formed using simple tooling. These stiffeners were formed to the desired configuration and required no additional sizing or shaping following removal from the mold. The weld-brazing process by which the stiffeners were attached to the skins utilized spot-welds to maintain alignment and no additional tooling was required for brazing. The superplastic formed/weld-brazed panels having complex shaped stiffeners developed up to 60 percent higher buckling strengths than panels with conventional shaped hat stiffeners.

The superplastic forming/weld-brazing process was successfully scaled up to fabricate full-size panels having multiple stiffeners. The superplastic forming/weld-brazing process was also successfully refined to show its potential for fabricating multiple-stiffener compression panels employing unique stiffener configurations for improved structural efficiency.

REFERENCES

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2. Bales, Thomas T.; Royster, Dick M.; and Arnold, Winfrey E., Jr.: Development of the Weld-Braze Joining Process. NASA TN D-7281, 1973.